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INVESTIGATION OF FREQUENCY DIVERSITY EFFECTS ON METEOR SCATTER LINKS

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9 January 1991

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13. ABSTRACT (Maximum 200 words)

Results of measurements of frequency diversity effects on the USAF Geophysics Laboratory meteor scatter bed test in Greenland are reported. The investigation included three field campaigns over two test links to acquire meteor scatter signal data and a series of special purpose statistical analysis procedures were developed. Diversity effects have been evaluated for frequency separations between 0.3 and 4 MHz at path lengths of 1200 and 700 km. The morphology of the results are described. Dual close-spaced frequency diversity seems to offer a limited improvement of channel properties and no frequency separation dependence was found. The apparent lack of monotonic frequency dependence leaves questions as to physical causes of variability. It is speculated that day to day changes in the neutral atmospheric density, high altitude winds and sporadic E-layer ionization should be investigated as candidate mechanisms.

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Contents

Illustrations

Investigation of Frequency Diversity Effects on Meteor Scatter Links

1. INTRODUCTION

This report presents results of measurements of frequency diversity effects performed with the USAF Phillips Laboratory's (formerly Geophysics Laboratory) meteor scatter test bed in Greenland. The test bed consists of two diagnostic links. One link situated between Sondrestrom AB and Thule AB is 1210 km long, entirely within the polar cap, while the other, situated between Sondrestrom AB and Narsarsuaq, is 690 km long, traversing the auroral oval. The location of the test bed is shown in Figure 1. The links are intended for the study of meteor scatter propagation and communication at high latitudes. This study includes diurnal, day-to-day, and seasonal variability of the channel properties as well as the effects of ionospheric disturbances. The links operate at 45, 65, 85, and 104 MHz. Five element, horizontally polarized Yagi antennas and 1 kW of transmitter power are used for transmission. Crossed five-element Yagis in conjunction with dual channel, phase locked loop receivers are used for reception of the horizontally and vertically polarized signal components. In addition, measurements at 35 MHz are performed on the Thule link. Previously, measurements have been performed at 147 MHz on the Thule link as well, but these were concluded after two years of successful data collection. The signals received by the test bed receivers are digitized with a time resolution of 10 msec and stored for analysis at GL. A range of propagation and communication statistics are routinely produced. A detailed

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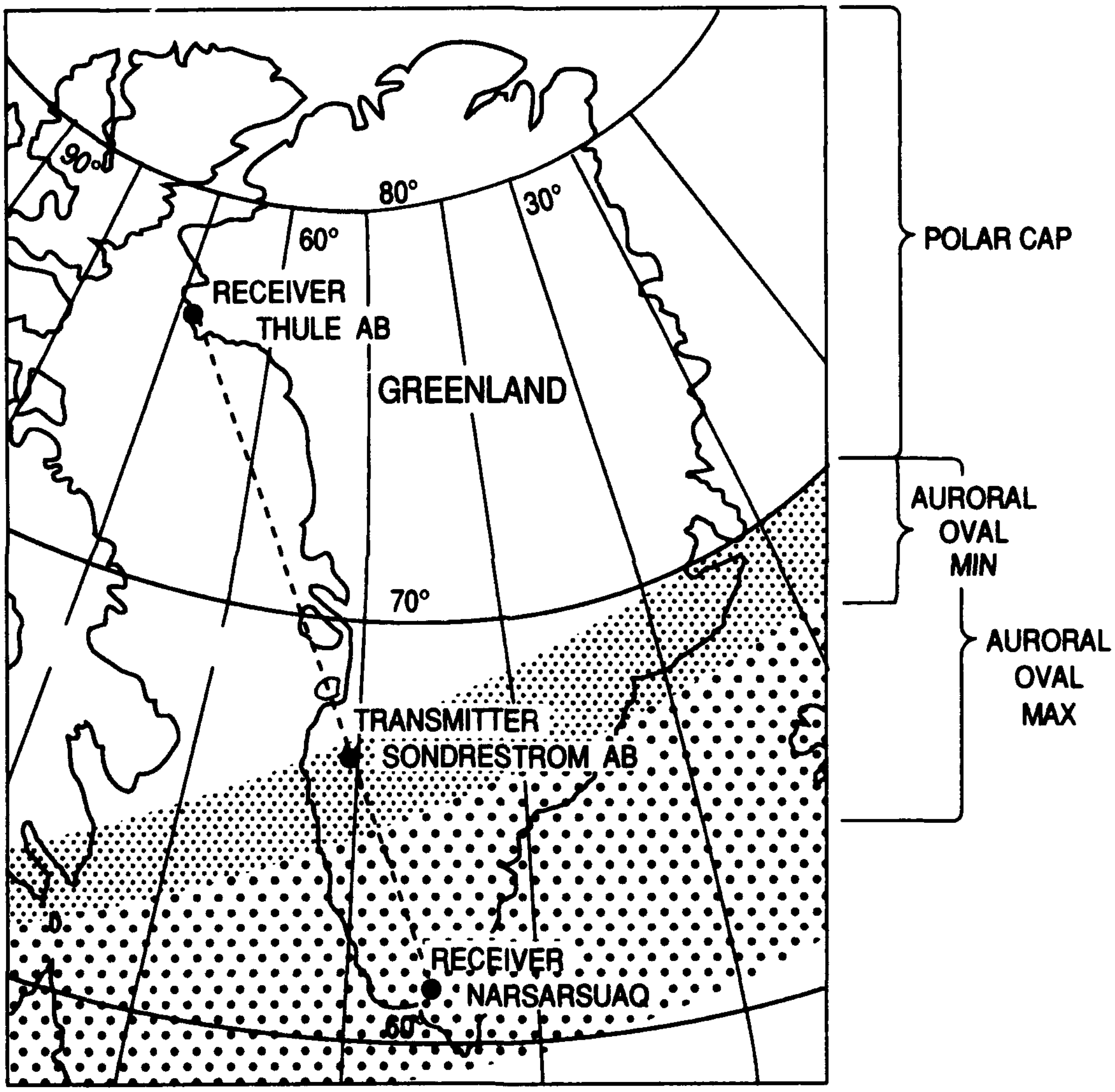

Figure 1. Location of the Phillips Laboratory Meteor Scatter Test Bed in Greenland

description of the Greenland test bed and results obtained with it are found in References 1, 2, 3, 4, 5, and 6.

The results in this report were obtained with the test bed during a series of special investigations of fading and frequency diversity effects with a time resolution of 0.5 msec. The investigations have included two field campaigns to acquire meteor scatter signal data, and a series of special purpose statistical analyses of the data. The results of the fading investigations are presented in Reference 7.

2. DIVERSITY IN METEOR SCATTER PROPAGATION

Fading radio channels that are sufficiently separated in space, frequency, time, or polarization can be more or less statistically uncorrelated. This fact is utilized in diversity reception techniques often used with fading radio circuits. The objective of diversity techniques is to make use of several received signals that constitute closely similar copies of some desired signal, to realize an improved signal level without resorting to higher transmitter powers or higher gain antennas. The increased reliability of a given radio circuit using diversity is only realized statistically, as it relies on the statistical nature of the fading processes of the propagation mechanism. To gain significant advantage, a sufficient degree of statistical independence of the fading must exist between the different signals in a diversity system. At least two channels are needed to obtain diversity gain, but higher order diversity utilizing more than two channels is commonly used with line-of-sight circuits.

A range of techniques exist for combining the signals from different channels in a diversity scheme. The simplest scheme consists of selecting the channel with the highest

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[1] Ostergaard, J.C., Bailey, A.D., and Bench, P.M. (1989) Experimental determination of waiting times for meteor trail returns of specified duration, February, March, June, September, December, PL-TR-91-2040, AFGL/LID, Hanscom AFB, MA 01731.

[2] Sowa, M.J., Quinn, J.M., Rasmussen, J.E., Kossey, P.A., and Ostergaard, J.C. (1986) A statistical analysis of polar meteor scatter propagation in the 45 - 104 MHz band. AGARD conf. on scattering in random media, CP.419, Rome.

[3] Ostergaard, J.C., Rasmussen, J.E., Sowa, M.J., Quinn, J.M., and Kossey, P.A. (1985) Characteristics of high latitude meteor scatter propagation parameters over the 45 - 104 MHz band. AGARD conf. on propagation effects on military systems in the high latitude region. CP.382, Fairbanks, AK.

[4] Ostergaard, J.C., Weitzen, J.A., Kossey, P.A., Bailey, P.M., Li, S.W., Coriaty, A.J., and Rasmussen, J.E. (1991) Effects of absorption on high latitude meteor scatter communication systems, *Radio Science*, Aug.

[5] Weitzen, J.A. (1989) USAF/GL meteor scatter data analysis program. A user's guide. Geophysics Laboratory GL-TR-89-0154, ADA 214988.

[6] Li, S.W. and Bailey, A.D. (1990) Antenna pattern description Geophysics Laboratory high latitude meteor scatter test-bed. Geophysics Laboratory.

[7] Weitzen, J.A., and Ostergaard, J.C., and Li, S.W. (1990) A high resolution statistical characterization of fading on meteor communication channels. GL-TR-90-0329, Univ. of Lowell, Center for Atmospheric Research, Contract No. F19628-88-K-0004, ADA235548.

signal to noise ratio at any given moment. If the signals are coherent, as they are when space diversity is used, combination may be performed at a suitable IF frequency, and post detection combination can be used with both coherent and non-coherent signals. Frequency and space diversity is traditionally used with microwave line-of-sight paths and troposcatter paths to combat fading and increase the availability of such channels from in excess of 90 percent to the 99.99 percent required for telephone trunk operation. The meteor scatter channel is inherently a very low duty cycle channel with a typical availability of 1 percent to 5 percent. The classical evaluation of diversity aimed at very high duty cycle channels that can be described as continuous processes, are therefore of limited use for discussions of diversity in meteor scatter propagation. The diversity improvement obtainable in meteor scatter propagation must be evaluated on a trail by trail basis. Some, but not all, meteor scatter signals fade within their short lifetime, and diversity improvement can be obtained within the lifetime of the individual meteor trail signals only if fades for different frequencies or different antenna spacings are sufficiently uncorrelated.

Four types of diversity are of interest in meteor scatter propagation:

* Space diversity with closely spaced receivers.
* Space diversity with widely spaced receivers.
* Frequency diversity with closely spaced frequencies.
* Frequency diversity with widely spaced frequencies.

The existence of close spaced diversity improvement for fading meteor trail signals was demonstrated and exploited with the COMET system in Europe, with four fold space diversity and antennas spaced several wavelengths. It was suggested in the theory presented by the Janet group in Canada in the late 1950's, that fading on long lasting meteor scatter signals can be due to warping of the trails by high altitude winds. This could produce more than one scattering portion of a given trail for a pair of communication terminals. Thus, the fading mechanism is essentially a multipath phenomenon. It follows from this that space diversity improvement potential should mainly be expected at the end of long lasting trail signals, whereas the start of the signals right after formation of the trails should exhibit less diversity improvement potential, as high altitude winds have not yet been able to warp the trail. Long lasting meteor trail signals often originate from overdense trails, and it is indeed known that these signals fade more often than do the usually shorter underdense trail signals .[7, 8]

Meteor scatter links using space diversity with widely spaced receivers rely on the directional properties of meteor scatter propagation. Meteor scatter links with sufficient spatial separation do not utilize exactly the same meteor trails for communication. Rather, the number of meteor trails used by both links in common decrease as the separation increases, until no trails are used by both links. In this situation the capacity of the system will be doubled, and a large increase in throughput is feasible if more than two receivers can be spaced enough to utilize essentially independent meteor trails. The necessary spacing is large, in the order of tens of miles, and the receivers must have a high reliability

[8] Weitzen, J.A. (1990) Study of the ground illumination foot print of meteor scatter communication. *IEEE Trans. Com.* **TC-38:4**. April.

communication network such as wire or line-of-sight links to merge the information from the independent receivers. This diversity scheme is therefore not diversity in the classical sense, but rather a networking scheme. A detailed treatment of this approach can be found in Reference 8.

Frequency diversity with closely spaced frequencies rely on the fading mechanism being sensitive enough to produce uncorrelated fading at frequencies separated by a few percent. Again, diversity improvement potential can only be expected if the trail signals fade. The meteor scatter process is very aspect sensitive, and the scattering portion of a given meteor trail can move very rapidly, like a glint from a spiderweb thread, even if the displacement of the trail itself is rather slow. Thus, it takes little trail warping by high altitude winds to produce the multipath geometry leading to fading. Figure 2 shows meteor trail signals received simultaneously at 45.1 and 45.4 MHz. The signals fade and differences in signal amplitude up to 30 dB are seen. This may seem surprising for a frequency spacing of only 0.7 percent. Thus, even very closely spaced frequencies can exhibit diversity improvement potential if the signals fade. Intuitively, frequency diversity effects should be expected at the end of the lifetime of trail signals where high altitude wind distortion will have had time to develop. But frequency diversity effects might also occur at the formation of the trail if other, low level scatter signals are already present in the channel. An example of meteor trail signals received simultaneously at 45.1 and 46.1 MHz exhibiting diversity effects during trail formation as well as decay are shown in Figure 3.

Frequency diversity with large frequency spacing, such as 20 to 60 MHz, does not offer much potential for diversity improvement in the classical sense. The scattering efficiency and signal endurance decrease rapidly with an increase in frequency, so many more signals are observed on the lower frequency of a widely spaced pair. Figure 4 presents examples of meteor trail signals received simultaneously at 45.1 and 104.1 MHz. A variety of ratios of peak received power is observed, and it is seen that the signal decay time is much faster at the higher frequency. Still, a combination of low and high frequencies can be useful to mitigate propagation effects other than frequency selective fading. These effects include elimination of excessive interference propagated through ionospheric reflections at the lower frequencies; and elimination of sporadic-E layer propagation at the lower frequencies if privacy and the directional properties of meteor scatter propagation are of importance. Also, the higher frequencies are less susceptible to ionospheric absorption, so frequency agility or high/low frequency diversity are of importance for survivable/enduring communication systems. This topic has been discussed in Reference 4.

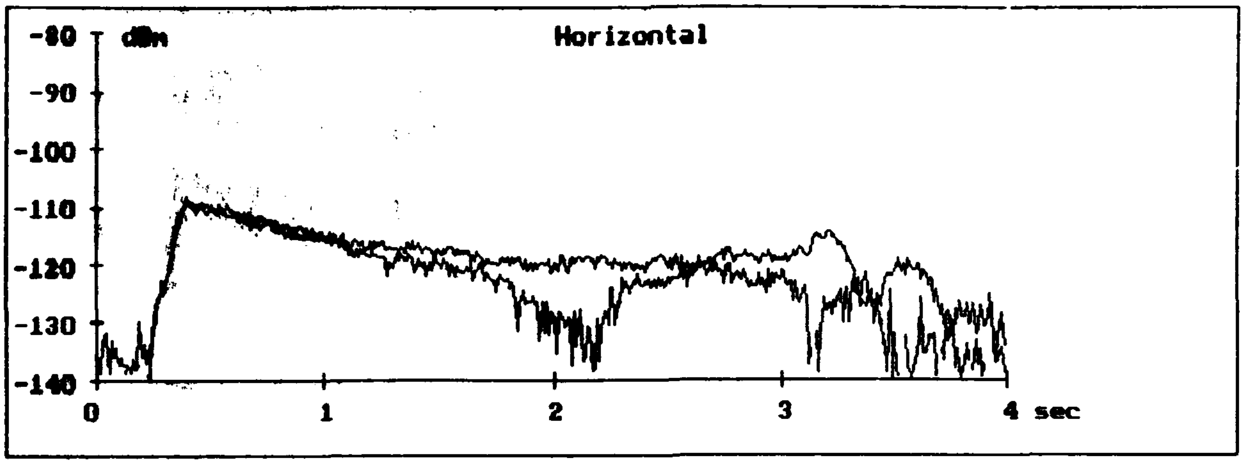


Figure 2. Meteor Trail Signals Recorded Simultaneously at 45.113 MHz and 45.413 MHz

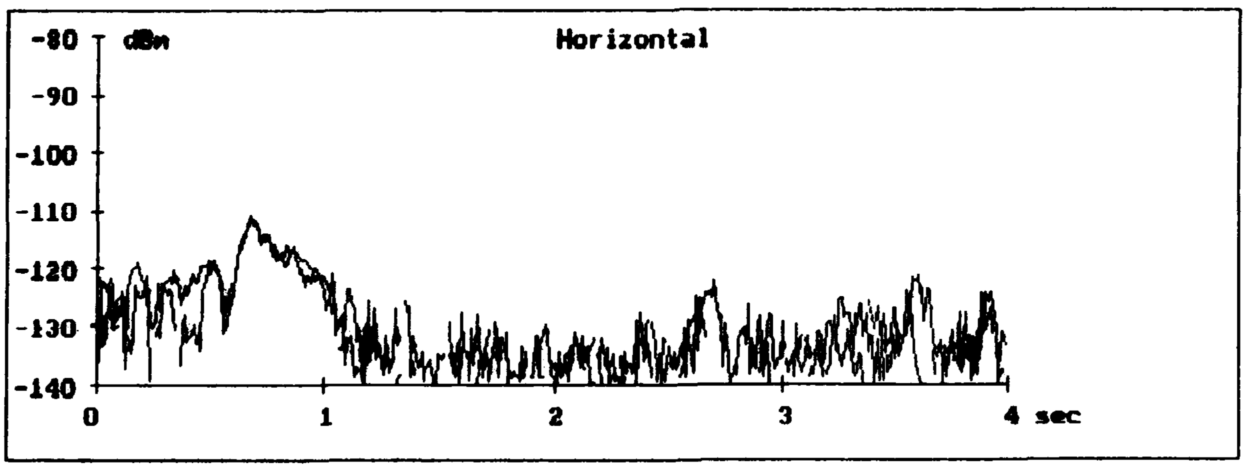
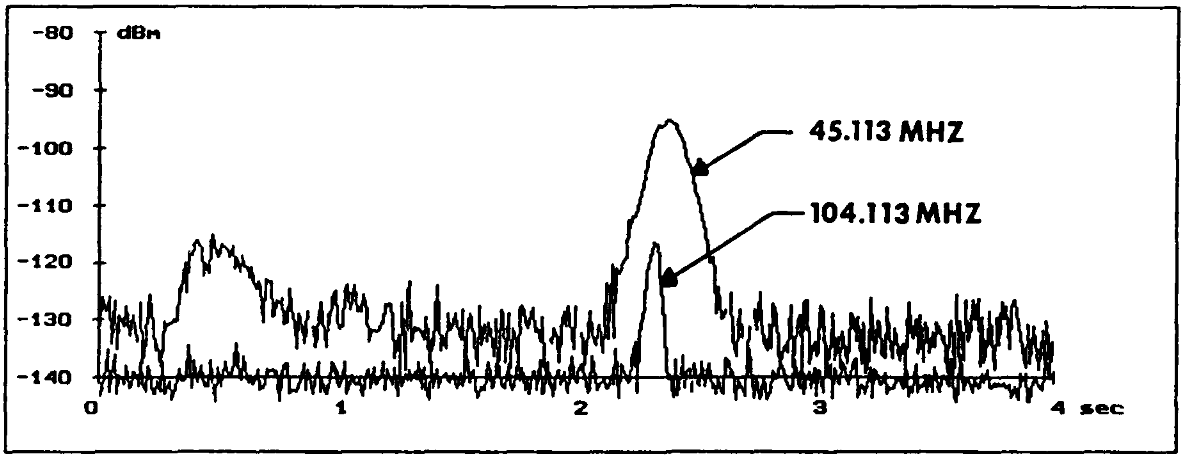
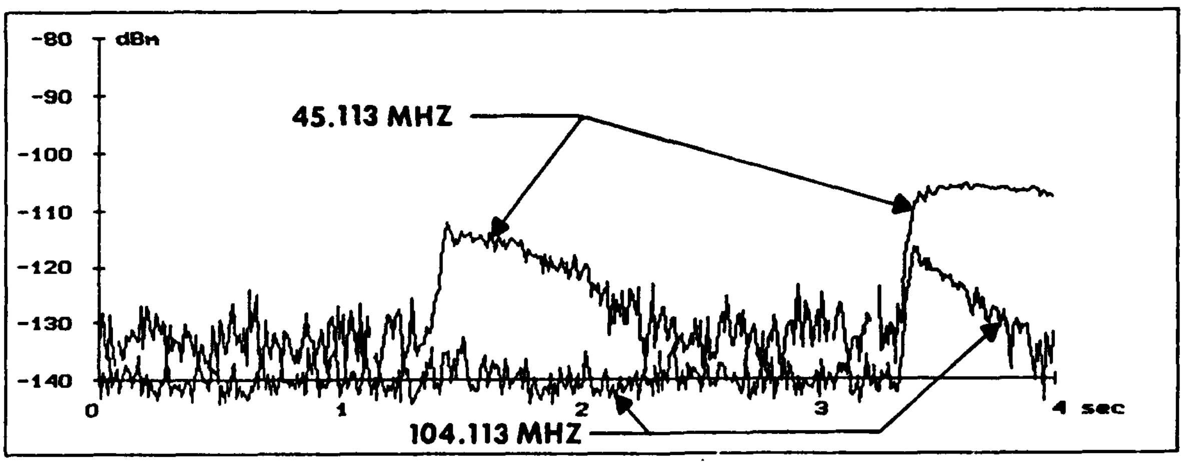


Figure 3. Meteor Trail Signals Recorded Simultaneously at 45.113 MHz and 46.113 MHz



station: Thule; frequencies 45.113 MHz, 104.113 MHz; bw: 2000 Hz
Time: 23/04/1990 07:10:12



station: Thule; frequencies 45.113 MHz, 104.113 MHz; bw: 2000 Hz
Time: 23/04/1990 07:10:24

Figure 4. Examples of Meteor Trail Signals Recorded Simultaneously at 45.113 MHz and 104.113 MHz

3. FREQUENCY DIVERSITY INSTRUMENTATION

Two independent transmitters, one for each frequency, were used for the frequency diversity measurements. They consisted of signal synthesizers driving 1 kW power amplifiers and five-element horizontally polarized Yagi antennas. The transmitted signals were continuous wave carriers without modulation. Separate antennas spaced one wavelength were used for transmission. The antennas were mounted approximately 1.5 wavelengths above the ground following computations of the radiation properties of the antennas including the influence of the foreground.[6] Although the existence of space diversity effects in meteor scatter propagation has been demonstrated,[9] very little, if any, space diversity effect exists with antennas this closely spaced.

Separate, phase locked receivers were used for the measurements at the two frequencies. The received signals were sampled at a rate of 2000 samples/sec, and the synchronous detector bandwidth was 1000 Hz. The resulting noise bandwidth of the receivers was thus 2000 Hz. Both receivers were fed from a single, horizontally polarized Yagi antenna through a power splitter. The calibration of the receivers was performed at the antenna port, such that the power splitter losses and the loading of the system by the receiver not being calibrated was included in the calibrations. The received power levels given in this report thus represent the received power at the antenna feed point.

4. THE MEASUREMENT CAMPAIGNS

Two measurement campaigns collected data for the investigation of fading and frequency diversity effects. The first campaign took place in April 1990 using the link between Sondrestrom AB and Thule AB. Measurements were performed at four different frequency spacings of 0.3, 0.7, 1.0, and 2.0 MHz in the 45 to 47 MHz frequency range. Each measurement lasted between 36 and 48 hours. The measurements took place during a low level polar cap absorption event. The 30 MHz zenith absorption as measured with the PL riometer at Thule was 0.2 to 0.9 dB throughout the period. Very few sporadic-E layer signals were observed except for a short period towards the end of the campaign. The signal sample collected is essentially a clean meteor scatter signal sample, a rare occurrence at 45 MHz during years of high solar activity.

The second campaign took place in July 1990 using the Sondrestrom AB to Narsarsuaq link. Measurements were taken in the 41 to 46 MHz frequency range at four different frequency spacings of 0.3, 0.7, 1.0 and 4.0 MHz. Each measurement lasted between 40 and 48 hours. However, the dominant mode of propagation during all but the hours between midnight and 0900 UT was sporadic E-layer reflection. Often these signals saturated the receiver for periods of up to 40 minutes. Such signal samples were discarded as they contained no fading or frequency diversity information and required excessive data storage. Data from other measurement periods, dominated by sporadic E-layer signals not saturating the receiver, were

[9] Bartholome, P.J. and Vogt, I.M. (1968) Comet - A new meteor-burst system incorporating ARQ and diversity reception. *IEEE Trans. Com.* **Com-16** (No.2) April.

kept. Thus, meteor signals were predominantly collected during a few night hours, but still a substantial number of signals were captured. Approximately 800 Mbytes of raw data were collected and stored on removable hard disks during the two campaigns.

5. DATA PROCESSING

The above discussion demonstrates the existence of frequency diversity effects, and in viewing a large number of meteor trail signals it is easy to find many examples of signals with rather spectacular frequency diversity effects. However, a large part of the total population of received signals do not fade and have no diversity improvement potential. Thus, statistical analysis is needed to quantify the frequency diversity improvement potential. Correlation analysis often used to characterize diversity effects for quasistationary channels may not be suited for analysis of meteor scatter propagation, which inherently exhibits a low duty cycle (1-5 percent) and other strategies described below have been employed in this study.

The raw data collected in Thule and Narsarsuaq was classified into meteoric and sporadic E-layer signal categories. Meteor trail signals have not been separated into underdense and overdense classes for this investigation, as these signal types occur at random and cannot be separated by a communication system. A data base program was then constructed and used to determine duty cycle and duration distributions for the low and the high frequency, and for both frequencies if the best frequency of operation was selected at any time. Also, duty cycle, since the start of a meteor trail signal have been computed for the low and the high frequencies individually, and for both frequencies if best frequency of operation was selected at any given moment. The statistics are determined as a function of time and received signal power. The time resolution is 10 msec for the duty cycle statistics. The distributions of duration and duty cycle since start of a meteor signal are sorted in 20 bins of 80 msec each. The received signal power has a resolution of 2 dB in the range from -90 dBm to - 140 dBm. Selected statistics showing the findings for the meteor trail signals are presented and discussed below.

6. THE STATISTICS

6.1 Duty cycles

The term: 'Duty cycle' denotes channel availability, that is, the percentage of the total time the signal level exceeded a selected threshold. When the best frequency of operation at any given moment is selected, the duty cycle must be greater than or equal to the duty cycle of the individual frequencies. Thus, the improvement in duty cycle can be computed as: Duty cycle with frequency selection/duty cycle for individual frequency. This ratio can be computed for both frequencies. The ratios can range from 1 if one of the frequencies dominates, to 2 if the two frequencies provide equal duty cycles without correlation. If one ratio is close to 1, then the other ratio may also be close to 1 if both frequencies fade at the same time, but it may

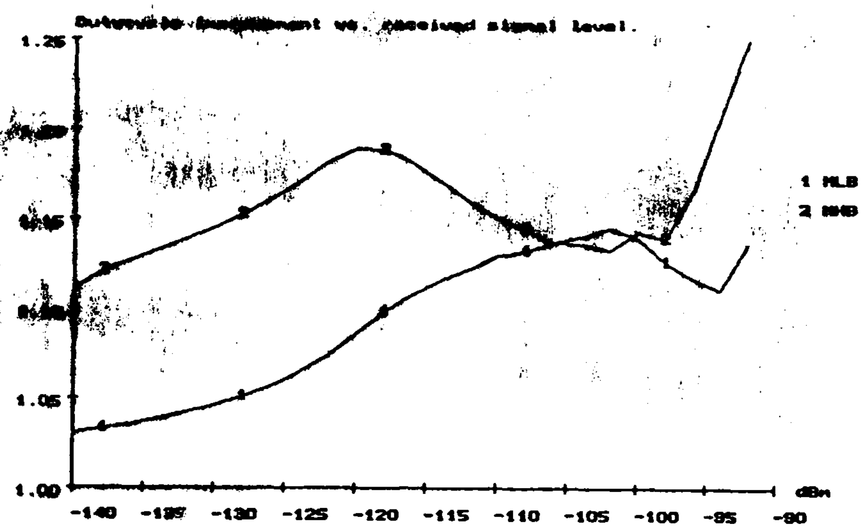


Figure 5a. Duty Cycle Improvement as a Function of Signal Level With a Frequency Spacing of 0.3 MHz. MLB and MHB signify duty cycle for both frequencies/duty cycle for low frequency and both frequencies/duty cycle for high frequency respectively.

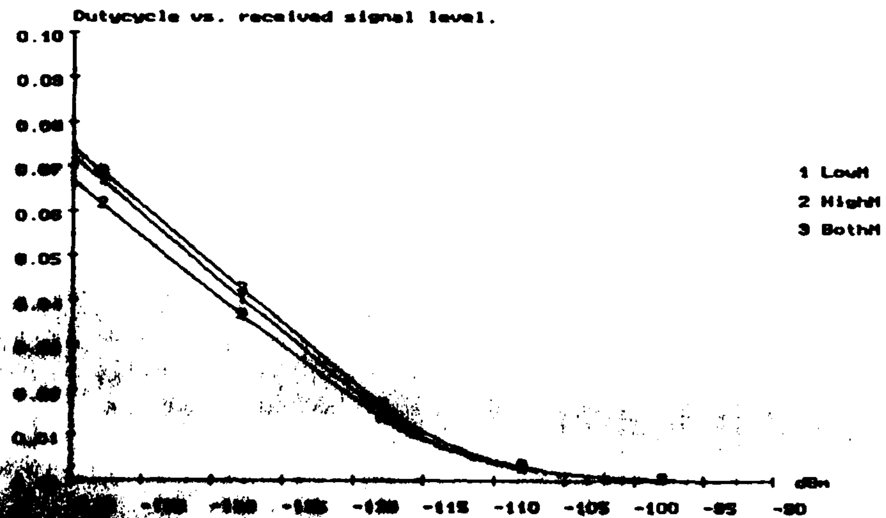


Figure 5b. Duty Cycle for the Low, the High and Both Frequencies as a Function of Signal Level. 0.3 MHz frequency separation

attain a high value if one frequency for some reason is vastly superior to the other. That is not expected to happen for closely spaced frequencies. It can still be envisioned, though, at very high received power levels, where the number of signals is small, and a few, uncorrelated fades can determine which frequency is superior even for a closely spaced frequency pair. The distribution of duty cycle for signals exceeding a received signal level at Thule is shown in Figure 5, for a 0.3 MHz frequency separation. It is seen that the duty cycle is largest for the combination of frequencies, and smallest for the high frequency. This fits the expectations well. The difference between the high and the low frequency duty cycles vary somewhat with frequency separation, but is in the order of a few percent of the duty cycle values. The ratios of the duty cycle obtained with frequency selection and the duty cycles for the individual frequencies are also presented in Figure 5. The diversity improvement obtainable by adding the high frequency to the low frequency is in the order of 3 to 15 percent, whereas the improvement obtainable by adding the low frequency to the high is on the order of 11 to 20 percent. The real diversity improvement is defined by the lower of the two ratios, as it is meaningless to start with the inferior frequency and add the superior to obtain diversity improvement.

The diversity improvement computed as described above is presented in Figure 6 for both Greenland links and for the frequency separations used during the campaigns. The diversity improvement is found to range from 3 to 20 percent regardless of frequency separation for the Thule link, and the improvement is not a monotonic function of frequency separation. The smallest improvement is found for the smallest frequency separation, and the largest improvement is found for the largest frequency separation at low signal levels. The intermediate frequency separations show the inverse relationship, that is, more diversity improvement was found at 0.7 MHz frequency separation than at 1.0 MHz frequency separation. At high signal levels, the largest diversity improvement is found for the smallest and the largest frequency separations, and the diversity improvement decreases to insignificant values for the intermediate frequencies.

The diversity improvement found on the Narsarsuaq link shows a small, but consistent monotonic frequency separation dependence at signal levels less than -110 dBm, and wide fluctuations above this level. In contrast to the Thule link, the largest diversity improvements show at the intermediate frequency separations. These unexpected findings illustrate some of the difficulties in determining meteor scatter propagation properties. In Figure 5 the total time of observation at a frequency separation of 0.3 MHz was 1700 minutes and during this time thousands of signals were acquired. However, at signal levels exceeding -110 dBm the duty cycle was found to be less than 0.5 percent or less than 8.5 minutes. This amount of data may not be enough to enable the determination of the diversity improvement magnitude or trend with suitable accuracy, when day-to-day variations in the meteor influx and upper atmosphere conditions cannot be accounted for. Thus, it takes very little data to demonstrate the existence of some feature in meteor scatter propagation, but very long term measurements are required to quantify these features. It must be concluded that the statistics generated for signals exceeding -110 dBm are most likely unreliable, and further discussions will be limited to signal levels of -116 dBm and -126 dBm. It should, however, be noted that the magnitude of the diversity improvement regardless of frequency separation did not exceed 15 to 20 percent for

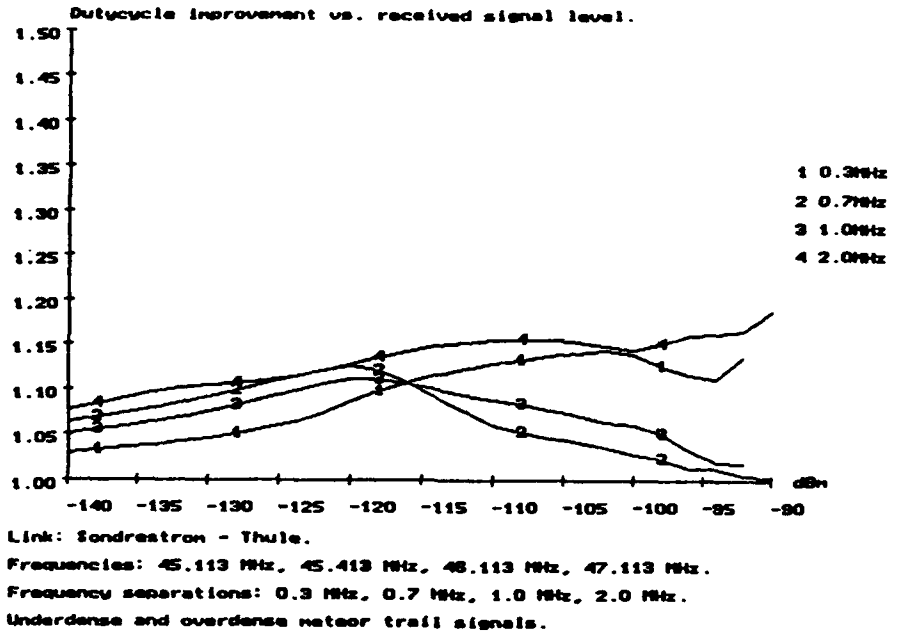


Figure 6a. Duty Cycle Improvement as a Function of Signal Level for the Various Frequency Separations at Thule

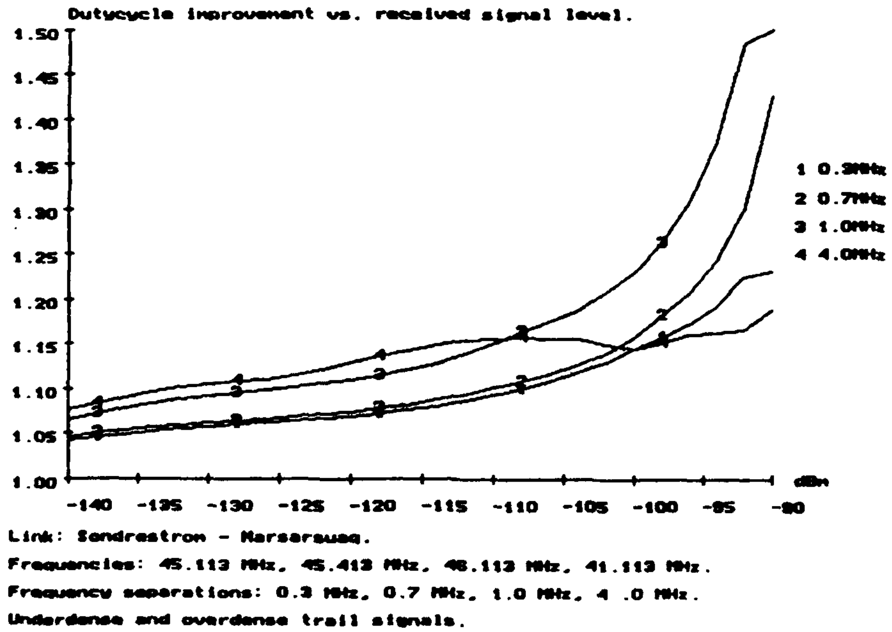


Figure 6b. Duty Cycle Improvement as a Function of Signal Level for the Various Frequency Separations at Narsarsuaq

signal levels less than -110 dBm. Thus, the measurements indicate that the long term average capacity of a meteor scatter communication channel increases little if closely spaced dual frequency selection diversity is used for reception.[10]

6.2 Durations

The term 'Signal duration' denotes a continuous period of time during which the received signal exceeds a given level. Meteor trail signals without fades will present one channel opening at any given power level not exceeding the maximum level for the event. Signals with fades will present a succession of openings separated by the fades. The distribution of durations thus describe the statistical properties of the length of channel openings. Diversity reception can increase the durations if the fades of the individual signals in the diversity scheme are uncorrelated to some degree.

Normalized distributions of duration for a frequency separation of 0.7 MHz measured in Narsarsuaq in July 1990 are presented in Figure 7 for received power levels of -126 and -116 dBm respectively. The duration distribution covers the range 0 to 1.6 sec in bins of 80 msec each. The high frequency has shorter durations than the low frequency for both power levels shown, and the longest durations are, as expected, obtained when frequency selection is used. The largest differences are seen for the lowest power level, -126 dBm. However, very little if any difference is seen for durations less than 160 msec. This interval contains 70 to 80 percent of the total durations. Thus, little improvement seems possible for shorter durations, but some diversity improvement may be obtained for the signals that exhibit long durations. These are not necessarily the same as the long lasting signals, which often exhibit a number of fades separating them into a string of signals with short durations.

Normalized distributions of duration when frequency selection is used are presented in Figures 8 and 9 for received power levels of -126 and -116 dBm as measured in Thule and Narsarsuaq at the various frequency separations. It could have been expected that the larger frequency separations would exhibit longer durations than the smaller frequency separations. That is seen not to happen. Very little if any difference is seen at durations less than 160 msec, the interval that accounts for the majority of signals, and no consistent frequency dependence is seen at longer durations. It may seem confusing that the normalization factors are larger for the high power level, -116 dBm distributions than for the low level, -126 dBm distributions. This is due to the fact that fading will create a number of separate channel openings for a given high level signal, but the fading may not be deep enough to affect lower power levels. Thus, the number of channel openings, regardless of duration, will increase with received power level until a power level is reached where the decreasing arrival rate begins to limit the number of channel openings.

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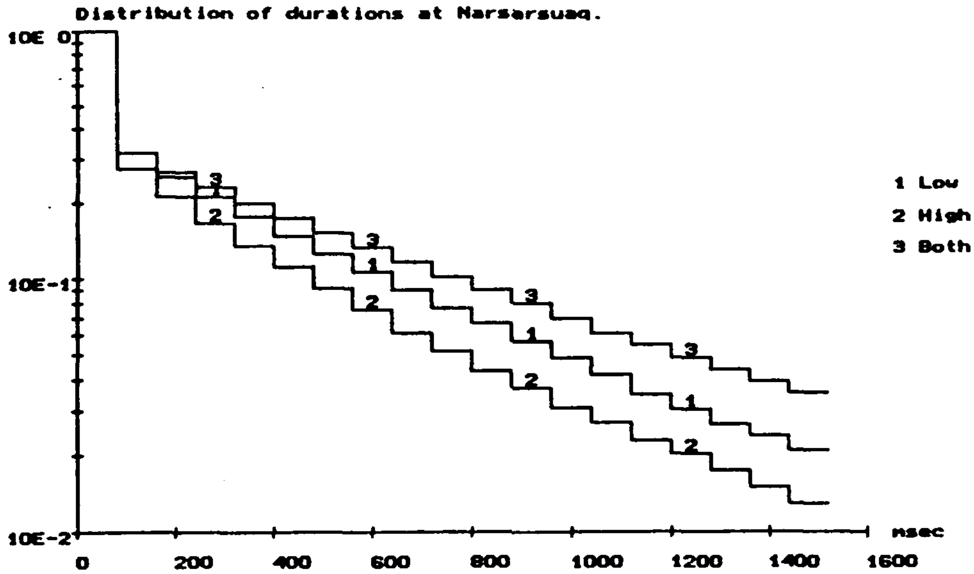
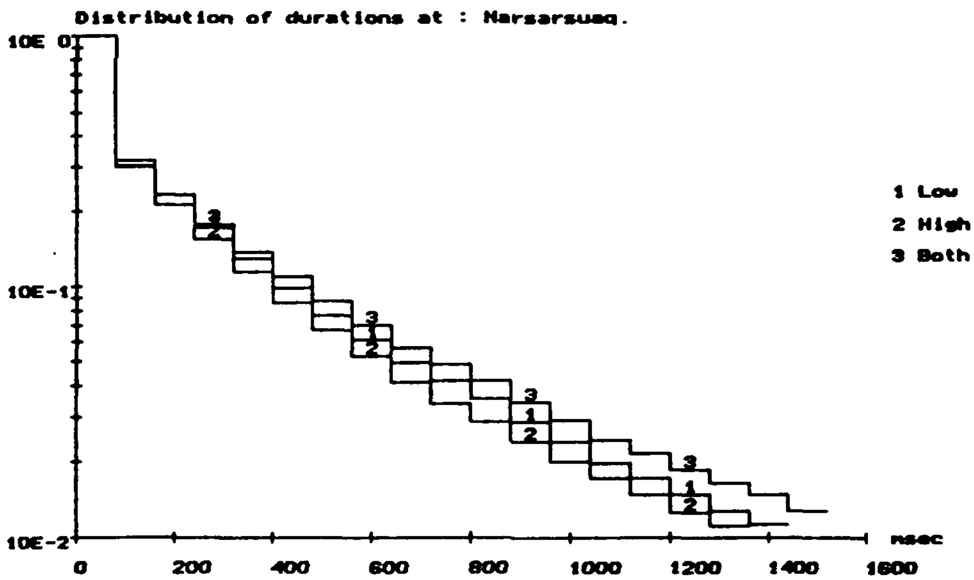
[10] Weitzen, J.A., and Ostergaard, J.C. (1990) A statistical characterization of fading on meteor communication channels, GL-TR-90-0362, ADA235148.

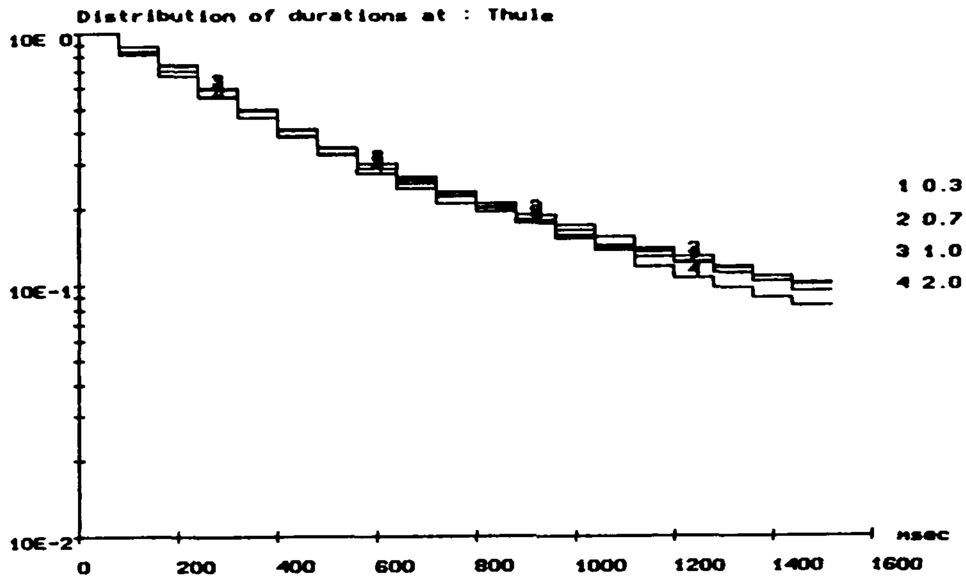


Underdense and overdense meteor trail signals.
Frequencies: 45.413MHz 46.113MHz.
frequency separation: 0.7 MHz.
Level -126dBm.
Normalizing factors: Low: 16723 High: 19046 Both: 14850

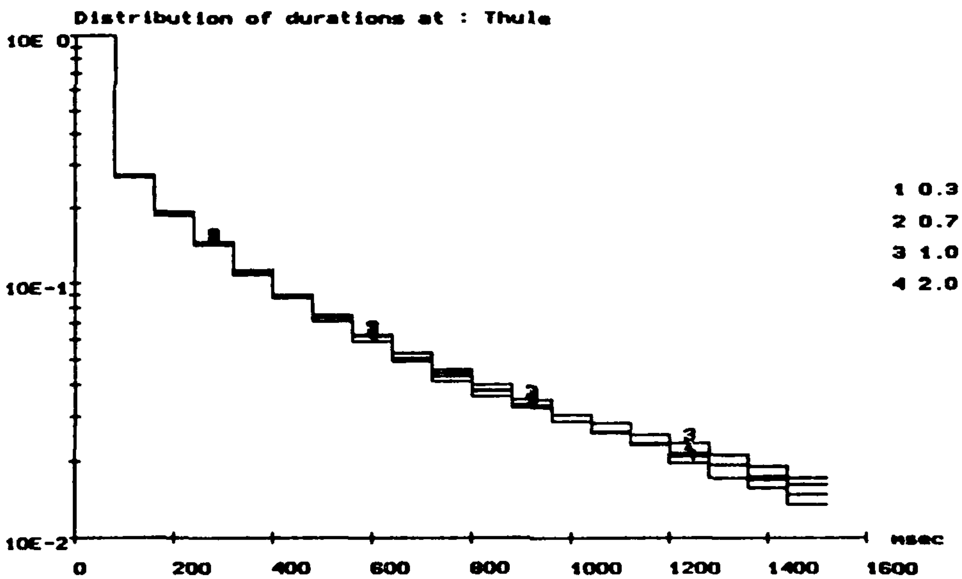


Underdense and overdense meteor trail signals.
Frequencies: 45.413MHz 46.113MHz.
Frequency separation: 0.7 MHz.
Level -116dBm.
Normalizing factors: Low: 14213 High: 13247 Both: 13825

Figure 7. Distributions of Signal Durations at Signal Levels of -126 dBm and -116 dBm for the Low, the High, and Both Frequencies at Narsarsuaq

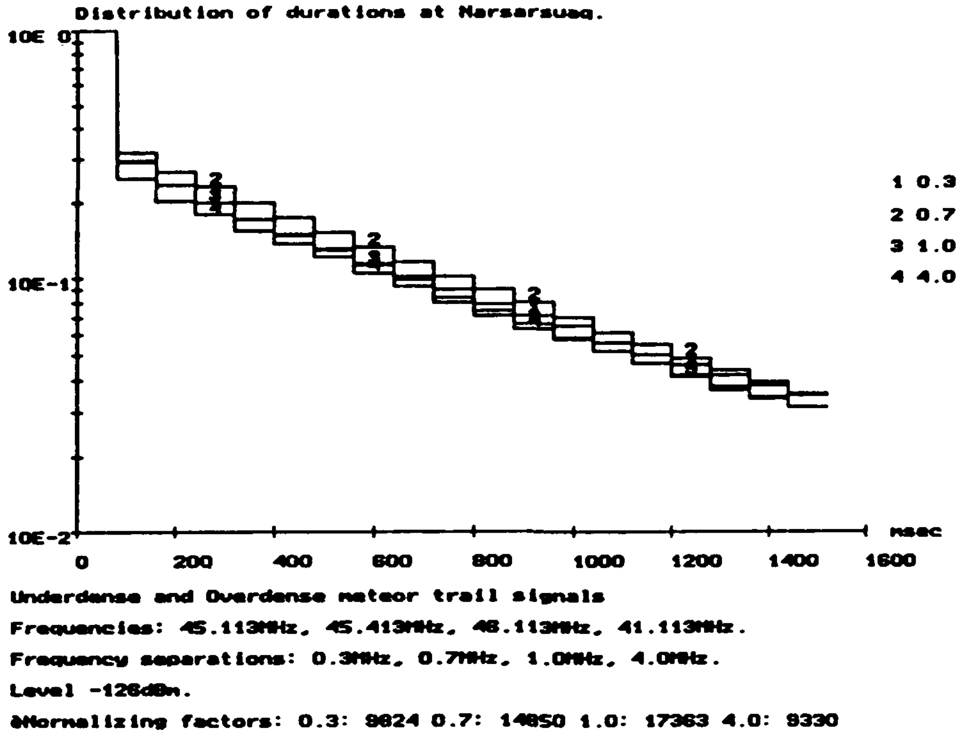


Underdense and Overdense meteor trail signals
Frequencies: 45.113MHz, 45.413MHz, 46.113MHz, 47.113MHz.
Frequency separations: 0.3MHz, 0.7MHz. 1.0MHz, 2.0MHz.
Level -126dBm
Normalizing factors: 0.3: 3277, 0.7: 4035, 1.0: 2697, 2.0: 3095



Underdense and Overdense meteor trail signals
Frequencies: 45.113MHz, 45.413MHz, 46.113MHz, 47.113MHz.
Frequency separations: 0.3MHz, 0.7MHz. 1.0MHz, 2.0MHz.
Level -116dBm
Normalizing factors: 0.3: 9527 0.7: 11751 1.0: 8127 2.0: 8210

Figure 8. Distributions of Signal Durations at Signal Levels of -126 dBm and -116 dBm for the Low, the High, and Both Frequencies at Thule



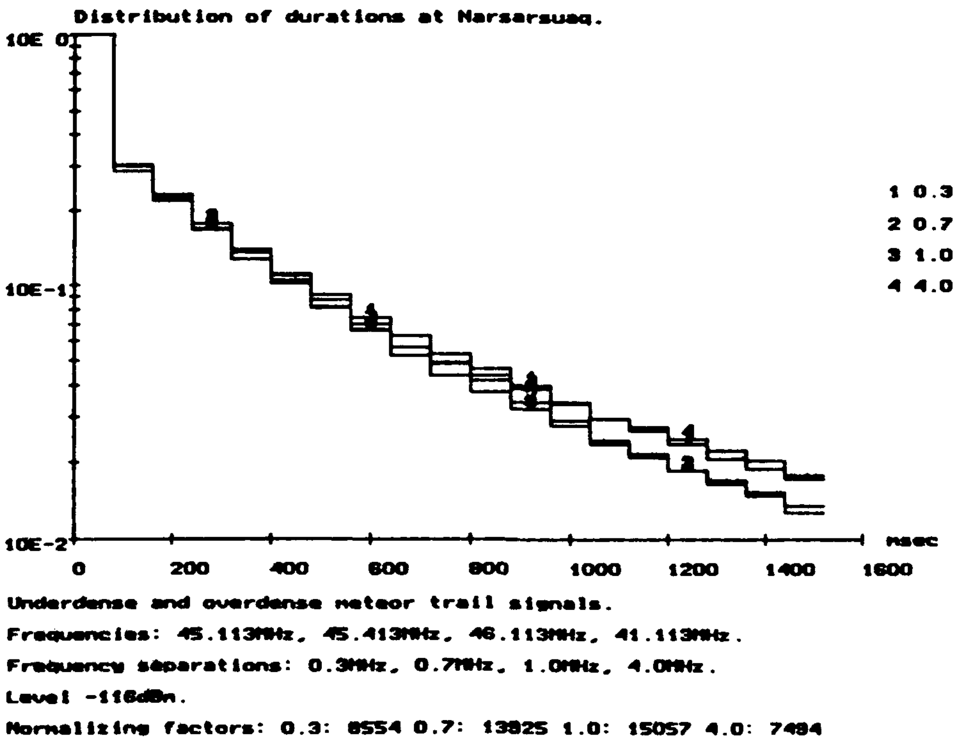


Figure 9. Distributions of Signal Durations at Frequency Separations of 0.3, 0.7,1.0,and 4.0 MHz at Narsarsuaq. The signal level was -116 dBm.

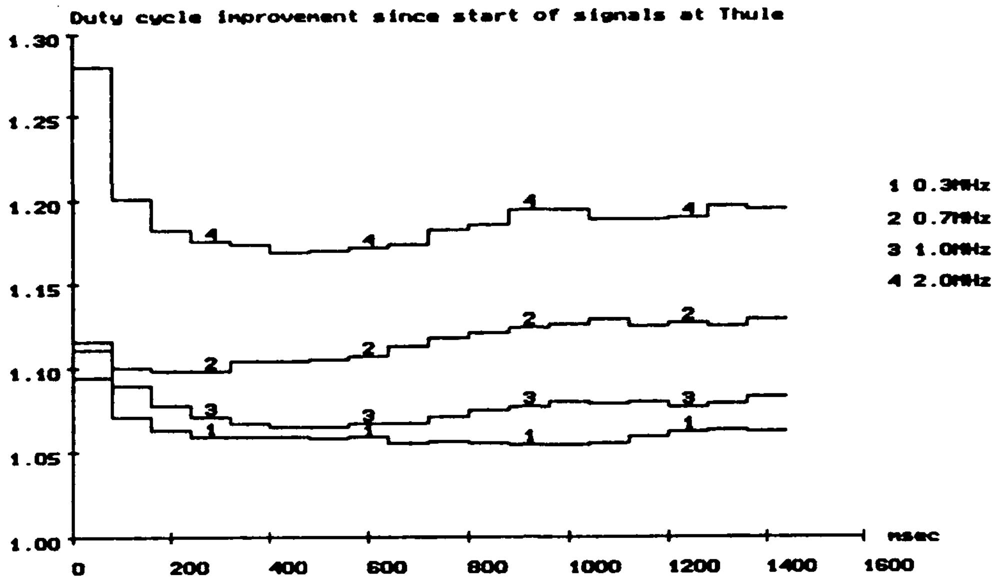
6.3 Duty Cycles Since the Start of Meteor Trail Signals

Visual examination of a large number of meteor trail signals gives the impression that some diversity effects are found at low signal levels during the formation of the meteor trails, and substantial diversity effects may be found for larger signal levels towards the end of long signals, when high altitude winds may warp the trails. Most signals are short though, and the diversity improvement as measured over the total population of trails as a function of time since the start of the signals will show where in time during the existence of the trails the most important diversity improvement occur.

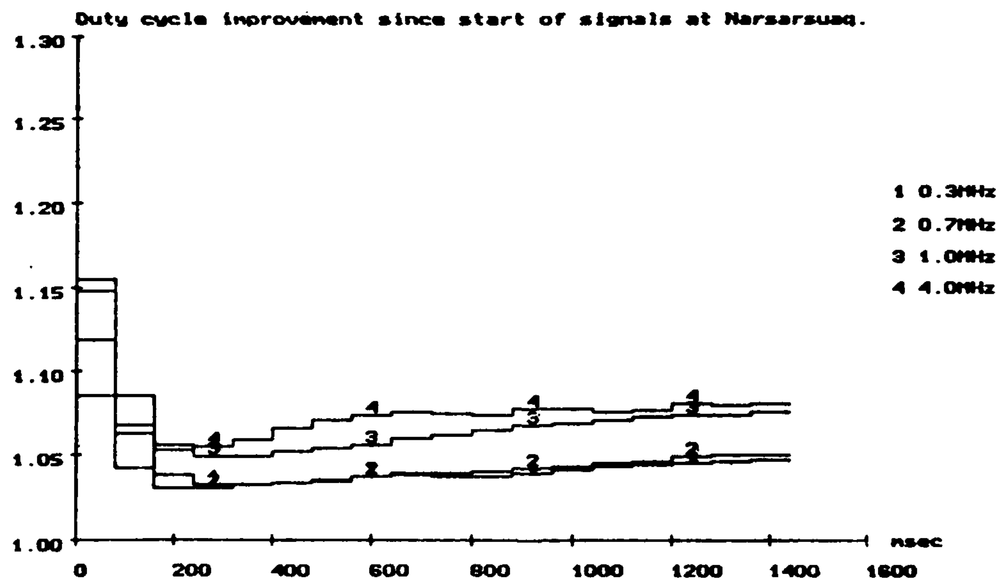
The duty cycle improvement since the start of meteor trail signals for frequency separations of 0.3, 0.7, 1.0, and 2.0 MHz measured at Thule in April 1990 and for frequency separations of 0.3, 0.7, 1.0, and 4.0 MHz measured at Narsarsuaq in July 1990 are presented in Figure 10 for a received power level of -116 dBm. The duration distributions cover the range 0 to 1.6 sec in bins of 80 msec each.

Improvements are seen, especially within the first 200 msec since the beginning of the signals. Minimum improvement is found at approximately 200 msec, and a slight overall increase with time expresses the improvement for long-enduring signals. Observations of raw trail signal data suggests substantial diversity improvements for long enduring signals. Such signals, however, only account for a small fraction of the total population of trail signals, and the overall diversity improvement is determined to a large extent by the many shorter lasting signals with few fades. This is not in conflict with the fact that the long lasting signals provide a major part of the connectivity, as the duty cycle improvement is a ratio. The substantial improvements found at less than 200 msec after the start of signals merely signify that the small fraction of the total connectivity found in this time interval can be improved by using frequency diversity. Also, no monotonic frequency dependence of the duty cycle improvement is found, although the largest improvements are found for the largest frequency separations.

The apparent overall lack of a frequency dependence of the diversity improvement raises speculation as to the causes of the variability of the fading mechanism. If a substantial day-to-day variation is present, then a much smaller frequency dependence may easily be masked. Excluding experimental errors, a number of mechanisms can conceivably contribute to a day-to-day variation. These include variations of the neutral atmospheric density at meteor trail heights, varying high altitude winds and the presence of varying densities of sporadic E-layer ionization. These could cause day-to-day variations of the diffusion of meteor trails as well as the formation of glints by trail warping.



Underdense and overdense trail signals.
Frequencies: 45.113 MHz, 45.413 MHz, 46.113 MHz, 47.113 MHz.
Frequency separations: 0.3 MHz, 0.7 MHz, 1.0 MHz, 2.0 MHz.
Signal level -116dBm



Underdense and overdense trail signals.
Frequencies: 45.113 MHz, 45.413 MHz, 46.113 MHz, 41.113 MHz.
Frequency separations: 0.3 MHz, 0.7 MHz, 1.0 MHz, 4.0 MHz.
Signal level -116dBm

Figure 10. Duty Cycle Improvements Since the Start of Signals Exceeding -116 dBm at Thule and Narsarsuaq

7. CONCLUSIONS

The data presented in this report describe results of frequency diversity measurements performed with the USAF Phillips Laboratory's Geophysics Directorate's meteor scatter test bed in Greenland. Frequency diversity effects have been evaluated for frequency separations between 0.3 and 4 MHz at two different paths of 1200 and 700 km. The morphology of the results are described, but little effort has at this time been devoted to possible explanations of some rather unexpected relationships.

The immediate impression when viewing a large number of meteor trail signals is that the frequency diversity effects occur during formation of the trails, that is, during the first 50 msec at low signal levels, and especially during the final decay of long-enduring signals. However, the statistics describing the diversity improvement as a function of the time since the formation of trails show this not to be the case for the total population of trail signals.

The major improvements are found within the first few hundred milliseconds after the formation of the trails. This most probably reflects the fact that the endurance of the majority of the signals is less than 500 msec, and the rather spectacular examples of large differences between high and low frequency signals found in the data sample for long-enduring signals are not descriptive of the full sample. The magnitude of the duty cycle and duration improvements range approximately from 5 to 20 percent.

No consistent frequency separation dependence of the diversity improvement was found in our measurements of duty cycle and durations, and the apparent lack of a monotonic frequency spacing dependence of the diversity improvement leaves questions as to the physical causes of the variability of the signal endurance and the fading mechanisms. It is speculated that day-to-day changes in the neutral atmospheric density, the high altitude winds, and the sporadic E-layer ionization should be investigated as candidate mechanisms. It has again been found that very long term measurements are needed to quantify meteor scatter propagation features, whereas little data is usually required to prove the existence of such features. Also, repeated measurements of frequency diversity effects should be performed simultaneously at all frequency spacings to eliminate the day-to-day variability of the propagation mechanism.

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